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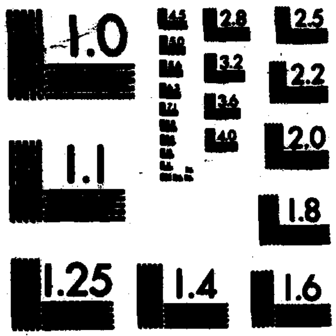

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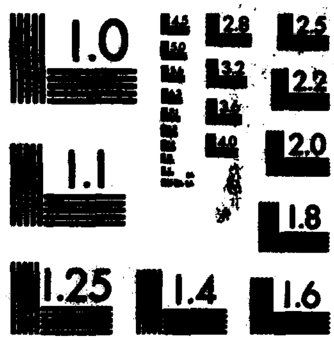

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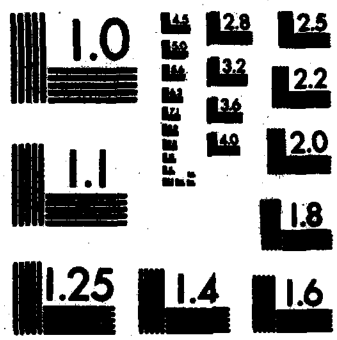

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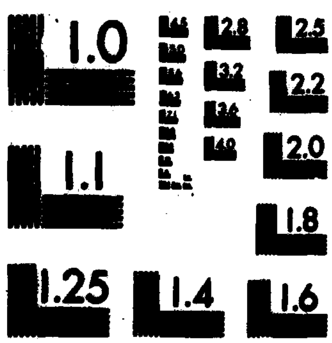

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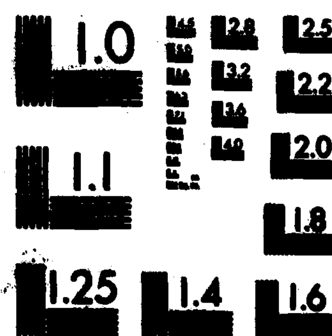

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Division of Applied Sciences
Harvard University Cambridge, Massachusetts

ANNUAL PROGRESS REPORT NO. 95

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I.1 Electronic Transport in Disordered Semiconductors. D. Montgomery, and H. Ehrenreich, Contract N00014-75-C-0648; Research Unit 1.

Semiconducting alloys such as HgCdTe, in which the band gap varies with alloy concentration, are of considerable interest as infra-red detectors. These materials have very high mobility and therefore excellent photoconductive properties. We have explored the reasons why the effects of alloying should be relatively weak, and in fact masked by impurity scattering at low temperatures and polar scattering at higher temperatures. An analysis based on transport theory within the coherent potential approximation has been made which indicates that the strength of alloy scattering is very weak because of the low density of states associated with the conduction band minimum in which the electronic transport takes place. This effect therefore is largely connected with the electronic structure.

Transport properties in this and related materials have been examined from a more general standpoint for a variety of band gaps extending from zero to positive values.[1] The validity of the Landau-Peierls criterion has been investigated for each case using Kane's $k \cdot p$ perturbation theory and the coherent potential approximation for an 8×8 model Hamiltonian. The results obtained should be useful in applications relating to other 3-5 and 2-6 semiconducting alloys. It appears that the weak scattering limit is valid in those materials for which the conduction band lies at $k = 0$ and when the minimum in question is not degenerate with others lying elsewhere in the Brillouin zone. This result promises to be helpful in the choice of semiconductors for various applications requiring fast circuits.

Reference

1. D. Montgomery (paper in preparation).

I.2 Electronic Structure of Disordered Semiconductors. K.C. Hass, H. Ehrenreich, and R. Lempert, Contract N00014-75-C-0648; Research Unit 1.

Some years ago this group developed combined interpolation schemes based on an empirical tight-binding and nearly free electron approximations, that were successfully applied to transition metals and their alloys to elucidate various electronic and magnetic properties. Recently similar schemes have been devised for semiconductors which are based purely on a tight-binding approach involving non-overlapping orbitals and empirically adjusted hopping integrals. Specifically, the scheme developed here includes interactions with second nearest neighbors as well as spin orbit effects. Disorder is treated within the coherent potential approximation and for that reason is confined to the atomic energies of the individual constituents. The latter are determined from self-consistent relativistic Hartree-Fock calculations. The effects of disorder on the hopping integrals are treated within the virtual crystal approximation. The parameters are adjusted by using self-consistent band structure results for pure parent compounds and optical data. The programs that have been developed to date apply to alloys derived from a zinc-blende structure. They have been thoroughly checked against existing calculations.

New results have been obtained for HgCdTe.[1] These show that the damping near the band edges is indeed weak and in particular that the electron mobility should be very high (in excess of 100,000 cm^2-volt/sec for compositions of interest in infra-red detectors) and the fundamental of optical absorption edge should closely resemble that of a pure crystal. During the coming year, we expect to use this approach for the following investigations: (1) a calculation of the electronic structure of a variety of 3-5 and 2-6 alloys. While a number of results already appear in the literature, we expect ours to be more reliable because the parameters have a firm base within existing physical information. Furthermore, we hope to use these results to investigate the questions of the ultimate mobility that can be achieved in semiconducting alloys. This question is of great importance in the selection of materials suitable for fast semiconducting devices.. (2) Semiconductor-semiconductor interfaces will be explored in greater detail using more realistic models than in the previous work of Carlsson *et al.*[2] (3) The effects of impurities in semiconducting alloys on the electronic structure will be explored in order to ascertain the conditions under which impurity levels will appear in the band gap.

While it may not be possible to achieve significant progress in all of these areas during the coming year, it is expected that these activities will form part of a continuing program.

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I.3 Optical Properties of Disordered Semiconductors. K.C. Hass and H. Ehrenreich, Contract N00014-75-C-0648; Research Unit 1.

A proper calculation of the optical properties of disordered systems within the coherent potential approximation requires knowledge of the two-particle Green's function or the memory function.[1] During the past year, as part of an extended visit by B. Velický, the theory of the frequency-dependent, dielectric function for disordered semiconductors was worked out and explicit results were calculated using simple models for the valence and conduction band densities of states. This theory was based on a formalism developed by Velický during the course of his previous visit to Harvard more than a decade ago. Many of the results obtained were arrived at independently by Abe and Toyozawa (AT). These were based on the same basic formalism and appeared in preprint form at the time the present work was nearing completion.[2] However, a number of results differ from those of AT. Several aspects of the problem will be examined in greater detail, as will others not previously considered.

The optical properties of disordered systems differ from those of crystals in the breakdown of k-conservation, the existence of vertex corrections which produce correlations between electrons and holes, and the effects of random momentum matrix elements. Furthermore, there is a class of phenomena, which may be summarized under the rubric of "Urbach Tail effects", that are caused by sharp fluctuations in the local impurity potential. Such effects are not treatable within the CPA. They are analogous formally to electronic transport below the mobility edge in amorphous semiconductors which are particularly prone to such sharp fluctuations. Such effects of course are not treatable within the coherent potential approximation and have been neglected by AT. While it is not yet clear whether the Urbach effects are predominantly connected with this region, it is important to investigate these matters. The Urbach phenomenon is universal in semiconductors. In addition the resulting exponential absorption edge is responsible for the sensitivity of AgBr to visible light, thereby making possible the photographic process, and the sensitivity of amorphous hydrogenated silicon, a promising photovoltaic material, to sunlight. A number of explanations for this phenomenon have now been reported in the literature. A large variety of physical explanations have been proposed. While some linear combination of these undoubtedly corresponds to reality, thus far no convincing case for any *single* candidate has been made.

During the coming year it is also planned to examine the conditions under which vertex corrections resulting from the disorder and random momentum matrix elements (neglected by AT) can be of importance in materials of physical interest. At the present time it appears that none of the 3-5 or 2-6 compounds or alloys that are commonly used will be significantly affected. We hope to test this conjecture and to state conditions under which it is fulfilled.

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I.4 Interaction Between Phase-Slip Centers. J.M. Aponte and M. Tinkham, Contract N00014-75-C-0648 and NSF Grant DMR-79-04155; Supplementary Unit.

We have studied quasiparticle diffusion current and heating generated by a phase-slip center[1] (source) by measuring the change in critical current of other phase-slip centers at different distance from the source. Our sample consists of a long tin microbridge ($40\mu \times 1\mu$) with four side probes, all part of the same film (0.1μ thick), the geometry defined photolithographically. The distance between the probes was chosen to be of the order of the quasi-particle diffusion length so that only one phase-slip center nucleates in any of the five segments of the bridge when current is fed through the adjoining probes. The probes were made wider than the bridge to allow application of currents well above I_c of the bridge without loss of superconductivity in the probes. Decomposition of the measured ΔI_c into parts even and odd in the source current allows separation of heating from diffusive current effects. The nonequilibrium current effect is visible up to 20μ from the source, decaying exponentially with distance. Allowing for diffusive loss of quasiparticle current into the probes, the intrinsic decay length is about 10μ at $T = 0.99\ T_c$.

Reference

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I.5 Nonequilibrium Switching Phenomena on Picosecond Time Scales. D.J. Frank and M. Tinkham, Contract N00014-75-C-0648; Research Unit 2.

We are investigating the time scale for the appearance of a voltage drop along superconducting microstrips when their critical current is exceeded suddenly. Several approaches have been taken to observe this effect in detail in indium microbridges, which have not been studied in this way before. Using essentially the same techniques as were developed to study aluminum microbridges, we have observed the long time scale (2-100 nsec) effects in indium. Observed effects have included the development of multiple phase slip centers as a function of time, and the qualitatively correct dependence of the delay time on current when the critical current is only slightly exceeded.

In a collaboration with IBM, we have used their Josephson junction sampling circuits to observe the very fast responses of indium strips in the 10 psec to 10 nsec regime. In order to do this we have developed the necessary photolithographic techniques to deposit our In microbridges directly on their chips, between two pads provided for this purpose. This is the first time the sampler has been used for a scientific measurement, and it worked very well, providing better sensitivity and lower spurious signals than could be achieved any other way. Extensive computer simulations have been made, based on the theory of Schmid and Schön,[1] for comparison with the experiments. We find qualitative agreement, including the first known observation of the predicted initial inductive peak, and a reasonable account of the delay time before the start of the final voltage rise, but the observed rise-times to the fully normal state are much longer than expected. We plan to do further experiments to attempt to understand this effect.

Reference

1. A. Schmid, G. Schön, and M. Tinkham, "Dynamic Properties of Superconducting Weak Links," *Phys. Rev.* B21, 5076 (1980).

I.6 I-V Curves of Point Contacts. G.E. Blonder and M. Tinkham, Contract N00014-75-C-0648 and NSF Grant DMR-79-04155; Supplementary Unit.

A key element in our theory[1] for the subharmonic gap structure in superconducting metallic contacts, described in last year's report, is a thorough understanding of the mechanisms of current flow across a normal-superconducting (NS) interface. During the past year, we have made calculations[2] within the framework of the Bogoliubov equations which clarify the meaning of a gneeralized semiconductor picture, including the important role of the Andreev reflection process, and the generation of charge imbalance between pairs and quasiparticles at the interface. By including an adjustable delta-function potential barrier at the interface, the model can describe the continuous variation from metallic to tunnel-junction behavior.

Concurrent with our theoretical program, we have been carrying on experiments on Cu-Nb point contacts, as a model NS system. Our observed differential resistance curves[3] provide quantitative confirmation of the predictions of the theoretical model for varying barrier strengths, depending on the treatment of the point. We are also carrying on a collaborative effort with Dr. M. Octavio (at IVIC) to investigate the applicability of our results to the contacts he fabricates by dielectric punch-through in thin-film tunnel junctions.

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3. G.E. Blonder and M. Tinkham, in preparation.

I.7 High-Frequency Properties of Small-Area High-Current-Density Tunnel Junctions. W.C. Danchi, F. Habbal, and M. Tinkham, Contract N00014-75-C-0648; Research Unit 2.

We have started a program aimed at investigating the high-frequency properties of small-area high-current-density tunnel junctions, including the roll-off of the AC Josephson effect at frequencies above the gap frequency, photon-assisted tunnelling effects, and far-infrared mixer action. In order to see these effects at far-infrared frequencies, we need to have junctions with small RC times. Since we must have a reasonably high resistance, 10 to 100 ohms, to couple the radiation into the junction, we must make the capacitance, and therefore the area, as small as possible. Our junctions have areas of about 2×10^{-9} cm^2, the minimum attainable using optical photolithographic techniques. For resistances of 10 to 100Ω we obtain current densities in the range of 10^4 A/cm^2 to 10^5 A/cm^2. Junctions are fabricated using an oblique evaporation method developed at Bell Labs.[1] A base electrode of Sn is deposited first, followed by a layer of Ge which is evaporated at an angle so that it breaks over the edge of the Sn film. The edge of the Sn film is oxidized by a DC glow discharge in a pure oxygen environment, and finally the Pb counterelectrode is evaporated.

We find these junctions have excellent DC current-voltage characteristics. Using 10 GHz microwave radiation, we have observed Josephson steps up to 4 mV, which is more than twice the value for the sum of the gaps, $\frac{1}{e}(\Delta_{Pb} + \Delta_{Sn}) = 1.9$ mV, for those Sn-SnO-Pb junctions. They also cycle several times before failing, indicating that the Sn oxide is stable and mechanically strong.

We are now preparing to study their properties in the frequency range of 250 GHz to 2.5 THz, using the optically pumped far-infrared laser system designed by D. Weitz.[2] In our initial experiments we are using the strong Methyl Fluoride line at 604 GHz (496 μm). These small area junctions are placed at the center of a dipole antenna (fabricated photolithographically), whose length is chosen to be resonant at 604 GHz, taking into account the single crystal quartz substrate.[3] We also plan to investigate junctions fabricated at the end of long-wire antennas (also on quartz substrates).

In collaboration with Dr. L.N. Smith of Sperry Research Center, we are planning to study the far-infrared properties of Nb-Si-Nb junctions fabricated[4] at Sperry. Radiation will also be coupled into these junctions using lithographically-produced planar dipole antennas.

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I.8 Production and Characterization of Amorphous Semiconductors.

P. Ketchian, D.K. Paul, B. von Roedern, R. Weisfield, B.G. Yacobi, and W. Paul, Contracts N00014-75-C-0648, NSF-DMR-78-10014 and NSF DMR-81-08327; Research Unit 3.

Amorphous semiconducting films of Si, $Si_{1-x}H_x$, Ge, $Ge_{1-x}H_x$ and $Si_{1-x-y}Ge_xH_y$ have been produced by two methods. (1) r.f. sputtering of crystalline targets by Ar onto substrates of glass, quartz, Aℓ and c-Si held at suitable temperatures between o°C and 400°C. The preparation parameters varied have included the substrate temperature T_s, the partial pressure of Ar, the partial pressure of H_2, and the r.f. power; (2) by glow discharge decomposition of SiH_4, GeH_4 and appropriate mixtures of these two gases with H_2. We have also made preliminary depositions of $Ge_{1-x}Sn_x$ and $Ge_{1-x-y}Sn_xH_y$ by sputtering pressed powder targets of GeSn alloy in a plasma of $Ar + H_2$.

The films are analyzed chemically for their alloy compositions by electron microprobe. X-ray examination has been applied to verify amorphicity or to determine the existence and size of microcrystallites. The thickness is determined using a Sloan Dektak profile-meter or by edge-on viewing in an SEM. The relative H-contents are determined from the integrated area of the X-H wegging mode vibration near 500-600 cm^{-1}.

These films have been used for measurements of transport, phototransport, photoluminescence, optical absorption, field effect, drift mobility, and capacitance-voltage-frequency. A coherent, self-consistent explanation of the data has been sought in terms of a model for the densities-of-states in the bands and the band gap. In subsequent sections, only those measurements supported by the JSEP will be described. These include a study of the effect of doping in the transport properties of a-Si:H, a number of related papers aimed at upgrading the device quality of amorphous hydrogenated and oxygenated a-Si, and a comprehensive examination of the phototransport as a function of temperature and intensity of illumination.

I.9 Study of Transport in a-Si:H Alloys. D.A. Anderson and W. Paul, Contracts N00014-75-C-0648, NSF DMR-78-100014 and NSF DMR-81-08327; Research Unit 3.

In last year's report, we discussed an exhaustive examination of the conductivity and thermopower as a function of temperature of films of a-Si:H produced under a wide variety of conditions. A number of anomalies in the transport were described, which appear in our and all other investigations, and it was suggested that most of them could be explained on the basis of an appropriate model for the growth of thin films of the semiconductor. This model envisaged islands of a-Si with very little H and very few defects, joined by tissue that was both rich in H and full of defects. These two phases had different structure, chemistry, band structure and transport properties. Different conditions of preparation emphasized either islands or tissue, and on this basis many of the anomalies could be explained and in fact eliminated by suitable adjustment of the preparation parameters. This report has now been published.[1]

We have now also published[2] conductivity and thermopower measurements as a function of temperature on a series of r.f. sputtered hydrogenated a-Si samples doped with phosphorus. The controlled addition of different partial pressures of PH_3 to the $(Ar + H_2)$ sputtering gas results in films of conductivity orders of magnitude larger than in undoped films. The detailed curves of conductivity and thermopower versus temperature show kinks and structure which are similar to those found elsewhere in the literature, which encourages us to seek a common interpretation for them. The earliest explanation of such data, given by Spear and LeComber,[3] envisaged transport in the extended states of the conduction band at temperatures near 400 K and transport in a phosphorus-related impurity band at low temperatures. Other authors interpreted the various changes in slope of the temperature dependences as reflecting transport in extended states above 400 K, but transport in a P-related impurity band between 200 and 400 K. Thus, there was a clear disagreement concerning the transport mechanism in samples at room temperature and above, in a situation where the experimental data were quite similar. There was also, as a result, disagreement concerning the displacement of the Fermi level achieved by the Dundee group in their classic first experiments on doping a-Si. This is usually estimated from the difference in conductivity activation energy between undoped and doped samples, an erroneous procedure if the transport path changes from extended states to an impurity band when the material is doped.

We have therefore analyzed the totality of our conductivity and thermoelectric power data to seek the most appropriate model. Despite finding that neither of the above two models fits the data perfectly, we find a clear preference for the interpretation that only at high temperatures (higher than those used by the Dundee group of Spear) is transport in extended states found. Transport at and above room temperature, up to about 400 K, is in a P-related impurity band. We have been able to derive activation energies, conductivity prefactors and thermopower parameters for the two transport paths in rather satisfactory agreement with results published by Jan et al.,[4] Ast et al.,[5] and van Dong et al.[6] This interpretation has implications for several current measurements and interpretations: (1) the second transport path is attributed to a band of P-derived states about 0.3 eV below the conduction band edge. This is inferred to be caused by tetrahedrally-coordinated P atoms and is the analogue of the familiar P donor level in crystalline material. An analysis of doping levels and of subsidiary photoconductivity and photoluminescence data on the same samples has suggested that another very important band is created about 1.3 eV below the conduction band, and that this band is attributable, most probably, to a defect of the intrinsic network stabilized by the P-impurity. The fact that there is evidence for such a band at about the same energy, whenever any n-type dopant is incorporated, supports this interpretation. Such a band, lying in the lower half of the band gap, has a profound influence on recombination kinetics; (2) the transport mechanism in the upper P-derived band is of a hopping nature, but it cannot be established whether it is of the variable range or nearest-neighbor types.

In the overall model it has not been found to be necessary to appeal to any abrupt change of mobility such as is supposed to occur near a mobility edge. In neither temperature regime does the transport resemble the random-walk motion predicted to occur near a mobility-edge. Small-polaron formation cannot be ruled out in the transport attributed to the P-derived band, but this effect is by no means firmly established. Finally, the assembly of our data and those of other workers establishes with reasonable certainty that the P incorporation has shifted the Fermi level by at most 0.3 eV, much less than claimed in Spear and LeComber's work. (3) Hall-effect measurements on P-doped films have always shown an anomalous *positive* Hall coefficient. Despite this, the magnitude of the derived Hall mobility is often compared with that for diffusive motion of carriers in extended states and found to fit reasonably well. It now appears that the Hall experiments have been carried out in a temperature regime where transport is by electrons hopping through the localized states of the P-related donor band. In this situation, an anomalous sign for the Hall coefficient is not unexpected. However, the data should not be used to draw conclusions regarding transport in conduction band extended states.

Confirmation of the model described above has been amply provided by other measurements carried out in this laboratory under DOE-SERI sponsorship.[7] A brief description is included here for completeness. The Schottky barrier heights of undoped and P-doped a-Si:H were estimated both from the activation energy of the saturation current density (derived from the temperature dependence of the extrapolation to zero voltage of the forward biased current-voltage characteristic) and from the internal photoemission. The barrier heights are always about 0.3 eV lower in the P-doped samples. Moreover, the value of I_0/E_s (the ratio of pre-exponential factor of the current to the surface field) is lower by about a factor of 100 for the P-doped samples; this agrees with direct estimates of the difference in the σ_0's in $\sigma = \sigma_0 \exp[-E_\sigma/kT]$ for the undoped and P-doped samples. The totality of the results reinforces our interpretation of the existence of a second important transport path in doped material which must be taken into account in the analysis of all forms of transport.

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I.10 <u>Study of Conditions for the Optimum Configuration of Pseudogap States in Amorphous $Si_{1-x}H_x$ Alloys</u>. J. Blake, R.W. Collins, A. Lachter, G. Moddel, S. Oguz, D.K. Paul, P. Viktorovitch, R. Weisfield, B.G. Yacobi, and W. Paul, Contracts N00014-75-C-0648, NSF DM-78-10014 and DOE-SERI-XW-1-9358-1; Research Unit 3.

In order to study both the transport in the extended states of the conduction and valence bands, and the kinetics of recombination, it is essential to be able to estimate the gap density of states distribution in energy, and preferably also, to be able to control that density through appropriate choice of deposition conditions. We have continued a number of different types of experiment on several fronts of this large study. We have earlier listed the different parameters of our deposition technique, which have been systematically varied, and we have also described the range of characterizational and property measurements undertaken. Last year we discussed the effects on the gap state density of incorporation of several different contaminants, of the use of high H_2 sputtering partial pressures, and of He-ion bombardment and subsequent annealing.

Several investigators along the same lines this year received at least partial support from the JSEP.[1-4]. In the first of these papers[1] the results of a systematic study of correlations in the collection efficiency, depletion width, midgap density of states and energy gap in sputter and glow-discharge deposited amorphous hydrogenated Si Schottky diodes were reported. The correlation included the demonstration of an inverse relationship between the mobility-lifetime product for holes and the midgap state density, and also of an inverse relationship between the energy gap and the midgap state density.

In the second paper[2] a test was designed of the proposition (with which we disagreed from our earlier work) that the observation of a Si:H stretching vibrational mode at 2000 cm^{-1}, without the often-present 2100 cm^{-1} mode, was a reliable marker of good device material. By arranging to place substrates at different distances from the target of a sputtering apparatus, and therefore ensuring different degrees of ion and electron bombardment, we were able to demonstrate precisely the inverse effect: that material which displayed only the 2000 cm^{-1} mode *could* have inferior photoconductivity, photoluminescence and $\mu\tau$ products.

In the third paper[3] the study reported above was extended and the effects on the gap state density and the $\mu\tau$ product for holes of very large hydrogen concentrations, and of incorporation of phosphorus and oxygen were reported. All three of these incorporations led to increased state density in the lower part of the band gap, above the valence band edge, as judged from an order of magnitude deterioration of the $\mu\tau$ product for the minority carriers, the holes. This inferred increase in the state density above the valence band (the states responsible for trapping holes) is much larger than the increase in the state density near midgap. Consistent with the increased hole trapping, the electron photoconductivity is found to increase, again by an order of magnitude. This demonstrates explicitly the unwisdom of using the magnitude of the measured photoconductivity as a reliable indicator of a "clean" energy gap.

In the fourth paper[4] an extensive examination was made of the effect of incorporation of 1-6 atomic per cent oxygen on a variety of electronic and optical properties. The results were self-consistently interpreted in terms of a suggested modification of the gap density of states in a-Si and a-Si:H.

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I.11 Photoconductivity in Amorphous $Si_{1-x}H_x$ Alloys. G. Moddel and W. Paul, Contract N00014-75-C-0648; Research Unit 3.

A study was completed[1] of the steady state photoconductivity and the decay of the photoconductivity after the termination of illumination, as a function of intensity of illumination and temperature, of a wide variety of sputtered and glow-discharge-produced samples of a-Si:H. The electron drift mobility and its temperature dependence may be deduced from a combination of the two types of measurement referred to. The results show a variety of types of dependence of the photoconductivity, $\Delta\sigma$, under standardized conditions of illumination versus temperature, which can also to be found in different publications in the literature. The changes in slope of $\Delta\sigma$, and also extrema and dips and valleys versus $1/T$, have been tentatively attributed (by others) to details in the distribution of gap states with temperature and to changes in the dominant recombination mechanism. Our view is that it is quite hard to obtain a unique assignment of process with only these data. We consider that it is necessary to expand the available information in two ways: (1) by extending the measurements of photoconductivity decay to shorter times (in the nanosecond regime) since there are strong indications of a fast recombination process which can, on occasion, eliminate at least 50% the photoproduced carriers, and (2) by combining the present measurements with measurements of dispersive and non-dispersive mobility as displayed in time-of-flight measurements, and constructing a theory for both steady state and transient phototransport which takes account of time-dependent mobilities as well as recombination processes.

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1.12 X-Ray Scattering in Liquid Crystals. J. Collett, E. Chason, K. Chan, L. Sorensen, and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR-79-19479 and NSF DMR-80-20247; Research Unit 4.

Collaborative experiments with the group at M.I.T. (R.J. Birgeneau and J.D. Litster) to measure X-ray diffraction from structures of freely-suspended thin films in ordered smectic phase have continued. Although this experiment is primarily supported by the NSF under Grant DMR-79-19479, it receives ancillary support from JSEP and is directly related to other X-ray projects directly supported by JSEP. Initial studies on the material 70.7 were carried out at the M.I.T. rotating anode X-ray facility with the aid of a position-sensitive detector that was available there. Based on preliminary results obtained at that facility, the experiment was taken to the synchrotron in Hamburg, Germany (HASYLAB at DESY). A triple-axis spectrometer has been installed there by Dr. Jens Als-Nielsen of the Risø National Laboratory in Denmark. In collaboration with him an extensive series of X-ray diffraction studies were carried out on "thick" films of 70.7. In the present case "thick" means approximately 1000 layers or three microns thick. Previous work by H.S. Leadbetter[1] and colleagues indicated that in the ordered smectic phases of this material there was a phase transition from an hexagonal, close-packed structure (ABAB packing) to a second hexagonal structure in which the layers were placed directly above one another (AAA packing). In addition, in the latter phase subsidiary X-ray diffraction peaks, indicating a modulated structure, were observed.

With the aid of synchrotron radiation we were able to show that the transition mentioned above occurs through two intermediate phases. The first of these was clearly identified at Hamburg to be an orthorhombic phase. This project was continued in the Gordon McKay Laboratory on our return from Hamburg where we have since shown that the second phase is monoclinic.

The second result to come out of the synchrotron was clear evidence that the modulation consists of a single wave vector whose orientation is parallel to one of the reciprocal lattice directions. Further work on the relation between distortions in various phases is currently in progress.

As a direct result of the above mentioned experiment, support was provided by the Risø National Laboratory, Denmark for Professor Pershan to return to HASYLAB in October of 1981 to carry out a second synchrotron experiment on the "free surface" smectic samples that were developed in regard to the light-scattering experiment described separately.[2] Prior to receiving assurances from Denmark about the availability of these funds, foreign travel for this experiment was guaranteed by JSEP. JSEP funds were not used.

This experiment, which lasted only one week, obtained two major results. Firstly, it demonstrated the feasibility of a new technique for doing high resolution X-ray spectroscopy from the free horizontal surface of a fluid. In particular, in collaboration with Jens Als-Nielsen and his student, Finn Christensen,[3] we were able to show that the free surface of the liquid crystal CBOOA acts like an optical mirror for ~8 keV X-rays incident at approximately 1.5 degrees. The angle of incidence exactly equals the angle of reflection and the intensity of the reflected signal is related to the smectic ordering induced by the free surface at temperatures for which the bulk is completely nematic. The penetration length into the bulk is equal to correlation lengths previously measured for bulk nematic CBOOA.[4]

This was a complete surprise since the original purpose of the experiment was the hope that the "free surface" technique would enable us to produce highly oriented bulk materials that would facilitate X-ray studies of certain important physical properties of bulk phases. Although this was demonstrated, the scheduled time at the synchrotron did not allow detailed studies of both the surface and bulk effects.

In spite of this we were able to show that if the free surface smectic-A phase (which is relatively fluid) is carefully cooled into the solid-like smectic-B phase, it is possible to maintain the good alignment of the fluid phase. The advantage of the aligned smectic-B phase is that it appears to be a highly reflecting X-ray mirror that should be suitable for soft X-rays and since the smectic-B phase is solid, it can be rotated to any position and used in the same way as conventional monochrometers. Following the synchrotron studies, Als-Nielsen made preliminary measurements at the Risø Laboratory in Denmark and a manuscript on this idea has been submitted to *Applied Optics*.

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I.13 <u>Light-Scattering from Thin Smectic Films</u>. L. Sorensen and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR-79-23597 and NSF DMR-79-19479; Research Unit 4.

This project was held in abeyance during the current report period for lack of personnel. We hope to be able to continue making measurements in this project within the next year.

I.14 <u>Critical Elastic Properties of Free Surface Samples at the Nematic to Smectic-A Phase Transition</u>. M. Fisch, L. Sorensen, and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR-79-23597 and NSF DMR-79-19479; Research Unit 4.

Critical properties of the smectic-elastic constant B have been measured for 80CB,[1] 8CB, $\bar{8}$SF, 40.8 and mixtures of 80CB-60CB displaying reentrant nematic behavior.[2] For all of the pure materials, it was possible to fit the data to form $B = B_0(t)^{\phi}$ where $t = (T_{NA} - T)/T_{NA}$. Values varying from $\phi \simeq .30$ to .44 were obtained for the different materials, indicating that by this criterion the critical properties of the smectic-A to a nematic phase transition are *not* universal.

David Nelson and John Toner have recently proposed a theory in which the elastic constant B should be discontinuous at the transition.[3] With that in mind it was reasonable to fit the data to a form $B = B_0 + B_1(t)^{\phi}$. The difficulty in measuring B_0 is that it is usually very small in comparison with B_1 and consequently can only be detected for values of t that are impossibly small. In re-entrant nematic mixtures[4] of $(80CB)_x(60CB)_{1-x}$ it is possible to find concentrations at which B_1 is considerably reduced. With this in mind an experiment was designed and carried out. The conclusion was B_0 is definitely nonzero for certain range of concentrations.[2,5] Although this is consistent with the Nelson-Toner theory, the measurements would also be consistent with a first-order transition. Further measurements are necessary in order to discriminate between them. Two manuscripts were prepared on the basis of this work. The first of these was published as a letter in *Physical Review Letters*.[1] The second manuscript has been submitted.[5]

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I.15 X-Ray Scattering from Lyotropic Liquid Crystals. T. Urabe, Eric Chason, Eric Sirota, and P.S. Pershan, Contract N00014-75-C-0648; Research Unit 4.

We have previously developed techniques to make liquid crystals of dipalmitoyl-phosphatidyl choline-water mixtures for a narrow range of conditions.[1] During the past report period we have successfully been able to hydrate these crystals while maintaining their good mosaic distribution. In this way we have been able to observe two separate phase transitions as a function of either temperature or chemical potential of water. X-ray diffraction studies on these crystals have revealed near-perfect orientational order for the crystals in both the $L\beta$ and $L\alpha$ phases of lecithin at water concentrations of approximately 20%.

We are currently growing new samples that will be studied more exhaustively with our rotating anode X-ray diffraction facility.

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II. QUANTUM ELECTRONICS

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II.1 Nonlinear Four-wave Mixing in Vapors. A. Bogdan, M. Downer, L. Rothberg, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 5.

The effects of collision induced coherence in four-wave mixing, reported for the first time in the previous annual report, have been studied experimentally in more details. The results have been published in five papers,[1-5] which appeared during 1981. They are also described in the Ph.D. thesis of A. Bogdan,[6] who has joined Lasermetrics Corporation. Several details of the theory of third order nonlinear susceptibilities have been verified.[1-6] Earlier results on coherent antistokes Raman scattering after excited states have been collisionally populated has now also been published.[7]

The experimental arrangement has been improved (with JSEP funding), so that both c.w. dye lasers, pumped by one argon-ion laser, are now actively stabilized to 1 MHz r.m.s. linewidth. This eliminates instrumental limitations in the investigations of the extremely sharp collision induced resonance at degenerate or nearly degenerate frequencies! The latter correspond to Raman-type resonances between the hyperfine components of the ground state.

Parametric studies of the widths of these resonances are in progress. The residual Doppler broadening has been reduced by reducing the angles between the nearly forward propagating beams from about 6° to 1.5°. The residual Doppler is further reduced by increasing the helium buffer gas pressure. This is, to our knowledge, the first observation of collisional narrowing in a Doppler broadened atomic optical spectrum. Detailed line shape studies may yield further information about the nature of velocity changing collisions and collisional potentials in these atomic systems.

The detuning from the exact sodium resonances will be varied over a wide range, so that the transition from the impact regime to the quasi-static collisional regime may be studied in detail and compared with Grynberg's theory based on the dressed atom picture. A variety of buffer gases will also be used.

With the application of magnetic fields collision induced Raman type resonances between Zeeman sublevels of the ground state may be observable. The influence of collisional induced Zeeman coherence may be studied. This may clarify the nature of the residual widths of the (nearly) degenerate collision induced resonances.

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II.2 Two-Photon Absorption in Lanthanide-Doped Crystals. M. Downer, A. Bivas, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 5.

A report on quantitative measurements of the line strengths of three two-photon $4f^7 \rightarrow 4f^7$ transitions of $Gd^{3+}:LaF_3$ was published early in the year.[1] The work stimulated a far-reaching theoretical response by Prof. B.R. Judd of Johns Hopkins University.[2] The serious discrepancies between our results and the predictions of the standard theory of lanthanide transition intensities formulated by Judd, Ofelt, and Axe[3] are explained quantitatively in terms of novel third order contributions resulting from spin-orbit interaction among levels of the $4f^6\,5d$ configuration, which serve as intermediate states. No measurements by linear optical spectroscopy has shown the effect of such contributions.

Meanwhile, the measurements of line strengths were extended to 14 two-photon transitions of $Gd^{3+}:LaF_3$, including a detailed study of the polarization dependence of each transition. The pulsed nitrogen laser-pumped dye laser system was used for these measurements. Six of the transition intensities agreed with the standard theory[3] when enhanced by the revision of Judd.[2] The remaining eight transitions, however, exhibited strong anisotropy, anomalously large intensities, and in several cases violated the selection rule $\Delta J \leq 2$. A new theory based on crystal field mixing of levels of the $4f^6 5d$ configuration was formulated, and succeeded in explaining most of the anomalies. A report on this work was presented at the Gordon Conference on Nonlinear Optics and Lasers, and has been accepted for publication in *Optics Communications*.[4]

A similar study of Gd^{3+} in aquaeous solution has also been completed. A study of $Ea^{2+}:CaF_2$, which has the same electronic configuration as Gd^{3+}, is in progress. The effect of near-resonant intermediate $4f^n$ levels on two-photon absorption will be investigated in Tb^{3+} and other ions. Interference with the non-resonant contribution, which uses $4f^{n-1} 5d$ intermediate levels, should be observable.

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II.3 Laser-Induced Ordering Phenomena in Matter. T.W. Mossberg, Contract N00014-75-C-0648; Research Unit 5.

Work on a new experimental effort, intended to investigate various aspects of laser-induced ordering phenomena in matter, was initiated. This program is described in detail in the JSEP renewal proposal designated to start April 1, 1982. Basically, the objective is to study the nature and potential uses of order introduced into material samples by interaction with pulsed laser radiation. One potential application for optical memories has recently been described.[1] Since the work on this program was begun rather late in the reporting interval, we have not yet progressed beyond the building-up phase of it. As a first step, a high-repetition-rate, high-power excimer laser has been acquired (with JSEP funds) to pump a tunable dye laser. The dye laser has already been designed and is now being constructed. The set-up of the laboratory itself, involving an optical table, plumbing, electronics, etc., is well underway. The experimental facility being constructed should be of considerable use to other experimental programs in quantum electronics as well as the laser-induced ordering program.

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II.4 Picosecond Laser Interactions with Semiconductors. J.M. Liu, R. Yen, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 6.

During the past few years, the subject of pulsed laser interactions with silicon has received a great deal of attention due to its technological importance and the controversies concerning its physical mechanisms. The main controversy centered on whether the absorbed laser energy is transferred to the lattice during the pulse to create thermal equilibrium between the electronic system and the lattice. Obviously, picosecond pulses can provide most stringent studies on the mechanisms of energy transfer in pulsed laser annealing of semiconductors.[1,2]

Our work in the past year settled these controversies. The state of the silicon surface during and following the absorption of picosecond laser pulses was studied by optical reflectivity measurements with good temporal and spatial resolution.[3,4] The electron and lattice temperature during and following the pulses were determined by the emission of electrons and positive ions from the irradiated silicon surfaces.[5,6] These data establish a "thermal melting" model[4] that silicon can be heated above its melting point during a picosecond laser pulse. The energy relaxation time for a dense plasma in silicon is shorter than 10^{-11} sec.[2] and the electron and lattice temperatures remain the same on a picosecond time scale.[5,6]

Based on this thermal melting model, very high heating and cooling rates on a single crystal silicon surface can be achieved with picosecond pulses so that an amorphous layer can be formed with suitable laser wavelength at certain energy fluences.[5,8] The phenomenon has been shown to be an intrinsic effect of ultrashort pulsed laser interactions with silicon, which does not depend on the ambient conditions, nor on the native surface oxide layers of silicon.[7] A simple technique for *in situ* measurements of the highly focused beam spot sizes on the sample surfaces was developed[8] to absolutely calibrate the threshold energy fluences to within ±10%. The results are in excellent agreement with theoretical calculations based on the thermal melting model.[4]

Picosecond time-resolved transmission and reflectivity measurements on thin silicon films on sapphire substrates are currently in progress. The second harmonic pulses ($\lambda = 532$ nm) of a picosecond Nd:YAG laser system are used as pump pulses and the fundamental pulses at 1.064 μm are delayed at various picosecond time intervals to serve as probe pulses. Good spatial resolution is obtained by tightly focusing the probe pulses to one-sixth of the diameter of the pump pulses. Preliminary results show evidence for melting during picosecond pulses. Further data will be obtained to study the details of laser-silicon interactions on picosecond time scales. We also plan to do similar experiments on GaAs or other semiconducting materials by the same techniques.

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II. 5 Picosecond Laser Induced Emission from Metals. R. Yen, J.M. Liu, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 6.

During this annual reporting period an experiment was performed with the electronic emission induced by pulses of only 2 ps duration, i.e., an order of magnitude shorter than used in previous investigations. The facility used was that of Professor M. Salour in the Electrical Engineering Department at the Massachusetts Institute of Technology. The experimental apparatus, supported by the Air Force Office of Scientific Research at MIT, consists of a synchronous mode-locked dye laser producing 1 ps, 1 nJ pulse near 600 nm wavelength, pumped by a mode-locked argon ion laser. The pulses are amplified by four Q-switched dye laser .~plified, pumped by the second harmonic of a Nd:YAG laser. The output consisting of tunable two millijoule pulses with peak powers of a few gigawatts is doubled in frequency in a K.D.P. crystal. The photon energy of the resulting 2 ps pulses is 4.10 eV, higher than the work function of zirconium metal. The linear photo-electric emission pulses from this metal were detected. At power levels more than 4 GW/cm^2, the zirconium surface melts and shows damage by subsequent visual inspection. In the range of 2-4 GW/cm^2, the photo-emission is thermally enhanced. The data are consistent with equal electron and lattice temperature, and rule out a hot conduction electron plasma in a cooler lattice. Thus the electron-phonon energy exchange time in zirconium metal is less than one picosecond. These results have been published[1] and this research project is now terminated.

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II.6 Time Resolved Studies of Intramolecular Energy Transfer. R. Sharp and N. Bloembergen, Contracts N00014-75-C-0648 and DAHG 29-81-K-0071; Research Unit 7.

In recently reported experiments,[1] we used a unique infrared laser system to investigate intramolecular vibrational energy relaxation in the molecule SF_6, excited by an infrared multiple photon absorption process (IRMPA). Our investigation made use of our advanced capability for generating picosecond pulses at CO_2 laser wavelengths to time-resolve the ν_3 node absorption profile of SF_6, subjected to an IRMPA heating process in a collisionless environment. The results of this study indicated that energy was distributed throughout the molecule in essentially a thermal manner within the 30 psec pump pulse duration.

In order to conduct a more thorough investigation into the nature of intramolecular vibrational energy relaxation and internal vibrational energy distributions, we have recently completed a series of experiments[2] on the molecule C_6F_5H. By virtue of having *two* infrared active modes accessible to the CO_2 laser wavelengths, we are afforded the use of a second diagnostic in the study of energy randomization. Since we have two synchronized CO_2 lasers, we can, on a picosecond time scale and in a collisionless environment, determine whether energy deposited in the high frequency mode 7a of this molecule (at 1077 cm^{-1}) rapidly equilibrates with a lower frequency mode 20b (centered at 950 cm^{-1}). Our results reaffirmed previous behavior found in SF_6. That is, not only did we discover that energy deposited in the mode 7a of C_6F_5H equilibrate within the 50 psec pump pulse duration with the lower frequency mode 20b, but also that the overall resultant energy distribution was apparently statistical, or thermal, in nature.

The results of the SF_6 and C_6F_5H work have also generated interest[3] in the field of intermolecular collisional processes. Collisional relaxation rates as fast as 2 nsec-torr, implying very long range intermolecular interactions, have been found in the vibrationally excited states of SF_6 and C_6F_5H. Presently, we are conducting further experiments to identify the nature of these processes.

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II.7 Infrared Multiphoton Excitation of Excited Electronic States in Molecules. J.Y. Tsao, I. Burak, and N. Bloembergen, Contracts N00014-75-C-0648 and DAHG-29-81-K-0071; Research Unit 7.

Studies of the infrared multiphoton (IRMP) excitation of molecules in excited electronic states have added a very sensitive detection tool, visible fluorescence, to current diagnostics. The phenomenon of inverse electronic relaxation (IER) in $CrO_2C\ell_2$, in which the IRMP pumping of the ground electronic level leads to population of excited electronic levels and visible fluorescence, has been extensively investigated.[1] This work settled the controversy surrounding the origin of the induced luminescence. Both the parent molecule and at least two dissociation fragments contribute to the luminescence. Thus IER of the parent is confirmed, but there are processes involving dissociation.

Previous work on NO_2 with synchronized picosecond CO_2 and Q-switched ruby laser pulses showed the first known direct evidence of IRMP pumping of an excited electronic state.[2] Since that report extensive work has been done to elucidate the dynamics of the process. Because of the strong coupling of the vibronic levels of the excited electronic states with the high energy vibronic levels of the ground electronic state in NO_2, visible excitation results in the creation of a molecule in the ground electronic state and a high degree of vibrational excitation, with a small admixture of excited electronic state character. One can then probe these excited states with an IR laser to check for the existence of a vibrational quasicontinuum. We have found that though the infrared resonances are very broad ($\geq 150\ cm^{-1}$) the density of states is not large enough for true quasicontinuum dynamics in NO_2 below the dissociation threshold.[3]

Much of the work on infrared multiphoton excitation of excited electronic states of molecules has been detailed in the Ph.D. Thesis of Jeffrey Y. Tsao.[4] Dr. Tsao has now joined Lincoln Laboratory in Lexington, MA.

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II.8 Multiphoton Vibrational Excitation of Molecules. T. Simpson and N. Bloembergen, Contracts N00014-75-C-0648 and DAHG 29-81-K-0071; Research Unit 7.

This work continues the systematic study of collisionless infrared energy deposition in polyatomic molecules. Specifically it is addressing the question of whether small polyatomic molecules, with three or four atoms are able to absorb many IR photons as larger polyatomics can. The aim is to elucidate the importance of the coupling of the pumped IR mode with the other vibrational modes of the molecule and to determine whether the coupling in small polyatomics is enough to create the quasi-continuum necessary for multiphoton absorption.

Work in several laboratories appears to indicate that significant collisionless multiphoton IR absorption in such molecules as OCS, O_3, SO_2, NH_3, HN_3 and DN_3, $CSC\ell_2$ and $BC\ell_3$ is possible, but the influence of collisions is easily underestimated. The study of several of these molecules is underway with our versatile CO_2 laser facility (pulses of 30 psec-100 nsec, peak power to 1 GW). Studies on OCS at high fluence (250 Joules/cm^2) and intensity (3×10" watts/cm^2) under essentially collisionless conditions indicate the average absorption of less than one photon per molecule. These measurements are at odds with some previously published results. Our new data have been published during this reporting period. Systematic experiments on other molecules are underway. Recent results on NH_3 indicate that true collisionless IR absorption is strongly dependent on laser peak power and that the molecular ensemble is not excited into the quasi-continuum. Details will be submitted for publication in the near future.

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III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION

Personnel

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III.1 Estimation Theory. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

Recent developments in estimation theory have focused attention on asymptotic expansions which describe the behavior of nonlinear filters which are, in some sense, close to being linear. In our paper[1] we use asymptotic expansions for the power spectra associated with nonlinear signal models which contain a small parameter in order to construct filters which are optimal up to a certain order in the expansion parameter. The results established there help to clarify the issues about what are sufficient statistics for nonlinear filtering problems and provide algorithms for the construction of asymptotically optimal filters.

The joint problem of system estimation and control (adaptive control) is solved for an interesting class of systems in Ref. 2. In this work a computationally feasible method for optimal adaptive control is worked out and the structure of the solution is compared with previous results.

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III.2 Diffusion Equations in Control. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

Understanding many problems in stochastic control and filtering depends on having an accurate picture of the properties of the diffusion equation which goes along with the underlying model. Of course in the case of Gauss-Markov models we have a complete picture of the solution space but for other models we lack even a qualitative understanding. In Ref. 1 below, a class of models involving singular perturbation is investigated and it is shown that through these techniques it is possible to get a very clear understanding of certain qualitative properties of an important class of diffusion equations. In Ref. 2, a second class of diffusions, arising this time from nonlinear models for stochastic signals which are very poorly approximated by Gauss-Markov processes, are analyzed and the background material is developed which allows for a precise understanding of certain "nonlinear" diffusions.

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III.3 Linear Systems. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

We have discussed earlier the problem of applying feedback compensation to a nonlinear system so as to make it behave in a linear way and have mentioned the relevance of this problem to aircraft control system design. Our earlier results on this problem addressed the question of determining which systems can be linearized by feedback in some neighborhood of an equilibrium point. In Ref. 1 below we lay the groundwork for extending this result away from a small set around an equilibrium point. More specifically, we characterize the global properties of systems, and the state space on which they are defined, which allows one to apply a feedback control law which linearizes them everywhere. These results depend on the fine structure of the linearized system, such as its controllability indices, observability indices, etc., and provide a quite detailed analysis of this problem.

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III.4 A Complete Solution for Two-Person, Single-Stage, Deterministic, Stackelberg Games. P. Luh and T.S. Chang, Contracts N00014-75-C-0648, N00014-79-C-0776, and NSF Grant ENG 78-15231; Research Unit 9.

A method was presented to solve two-person, single-stage, deterministic, Stackelberg games completely. The essence of our approach can be explained intuitively as follows. If the leader is extremely powerful, he can induce the follower to behave whatever he desires. However due to the fact that the leader has only limited information and limited control, and the follower's cost function is different from that of the leader's, the leader in general can only induce the follower's behavior to a "certain extent". In other words, there exists an *inducible region*, within which the leader can induce the behavior of the follower. If the team solution happens to lie within this region, it can be realized. This is exactly the case for most of the previous results. In general, however, *the best the leader can do is to optimize within this inducible region*. In Ref. 1, we delineate precisely the inducible region and provide a methodology to construct an incentive strategy.

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III.5 Necessary and Sufficient Conditions for Single-Stage, Partially Nested, Stochastic Stackelberg Games. T.S. Chang and P. Luh, Contracts N00014-75-C-0648, N00014-79-C-0776, and NSF Grant ENG 78-15231; Research Unit 9.

The above intuitive argument can be applied to stochastic problems, although it is difficult to delineate explicitly the inducible region. The paper,[1] focusing on single-stage, partially nested, stochastic problems, is a step towards that direction for stochastic games. It shows that it is possible to derive necessary and sufficient conditions for certain classes of stochastic problems, with results being complete in the sense of Ref. 2. It also stresses the intuitive appealing concept of an inducible region, and shows how the inducible region can be defined for stochastic problems. In contrast to deterministic problems where the inducible region consists of points, the inducible region for stochastic problems might consist of pairs of a function and a point. Finally, it sheds additional light in the understanding of stochastic Stackelberg games by demonstrating the importance of information structure to the solvability of a game, and pointing out the difficulties.

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III.6 Incentive-Compatible Resource Allocation Algorithms. Y.C. Ho and L.D. Servi, Contracts N00014-75-C-0648, N00014-79-C-0776, and NSF Grant ENG 78-15231; Research Unit 9.

Major effort last year was also devoted to the study of resource allocation algorithms which are incentive-compatible. The main problem here is that the center does not usually possess information which he needs for effective allocation. Yet the enterprises each have incentive to misrepresent such information in their own interest when asked by the center. Thus we have here a stochastic incentive problem with nonnested information structure. In particular, we were able to view from well known resource allocation algorithms, namely, the Arrow Hurwicz,the MDP, the Heal, and the Lindahl algorithms for private and public goods allocation from a unified viewpoint.[1] Using this approach, we accomplished,

(i) An incentive-compatible modification to the Heal algorithm for allocating private goods. This modification provides a dominant strategy for each enterprise to tell the truth and to enable the algorithm to converge to the optimum.

(ii) A general proof method for incentive-compatibility of these algorithms which does not require the explicit computation of the strategies adopted by the enterprises. From this approach we derived a much simpler proof of the convergence of the MDP algorithm.[2]

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IV. ELECTROMAGNETIC PHENOMENA

Personnel

Prof. T.T. Wu	Mr. M.F. Brown
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Mr. R. Bansal	Mr. H.M. Shen

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Application is also made of modeling techniques and the principle of similitude. Most practically significant problems in this area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researchers are concerned primarily with the properties of antennas and arrays and of the electromagnetic fields they generate in various practically important environments that lead to difficult problems with complicated boundary conditions. Examples include dipoles, traveling-wave antennas and arrays, crossed dipoles, and loops near the boundary between two media such as air and earth or sea water, and rock and sea water; dipoles in finite bodies composed of dielectric, conducting or layered materials; the currents in and fields between the conductors of a rhombic antenna; the fields in the complicated geometry of electromagnetic pulse simulators with and without scattering obstacles; and a novel type of large antenna array.

IV.1 Theoretical and Experimental Study of the Scattering from an Obstacle Above the Earth. H.-M. Lee, T.T. Wu, and R.W.P. King, Contracts DAAG29-79-C-0109 and N00014-76-C-0648; Research Unit 10.

The study of the electromagnetic field scattered from a conducting loop located above water has been completed.[1,2] Extensive numerical computations were carried out for different sizes of loops at different heights above the water. The agreement between the theoretical predictions and experimental data is good.

As pointed out in a previous report, the Sommerfeld integrals were the major obstacles encountered in the numerical computation. There has been some progress in obtaining a general analytic approximation to the integrals. In doing so, our understanding of the physics involved in the transmission and reflection of waves across a plane boundary has also greatly improved. Comparisons between approximate formulas for the integrals and direct numerical results are still lacking. However, formulas for the components of the electric field near the water-air interface both close to and far from a dipole source have been derived and compared with extensive numerical results with good agreement.[3,4]

For the scattering of a loop in free space, the original solution has been extended so that it can be applied to a tubular cylinder. Power series for the double series expansions in Tchebichef polynomials of the kernels of the coupled integral equations for the scattering current have been obtained. The singularity when the diameter of the cylinder was reduced to zero was found to be a logarithm squared, instead of just a logarithm. The implications have yet to be appreciated. A detailed investigation into the scattering of a finite tubular cylinder and the related problem of the axially driven antenna seems worth pursuing.

In a separate study, the currents in and the field scattered by a thin wire over a material half-space composed of earth, sea water, or lake water have been determined.[5] Full account is taken of the effect of the half-space on both the currents induced in the wire and on the scattered field. Distributions of current, back-scattering cross sections, and scattering patterns are given for both normal and non-normal incidence and with the incident field polarized in and perpendicular to the plane of incidence. The back-scattering cross section and the associated scattering patterns resemble those of the same wire when isolated but with greatly reduced amplitude. The data so far calculated show that the essential characteristics of the field scattered by a thin wire are preserved in the presence of a material half-space when the height d above the surface equals or exceeds about $d/\lambda_1 \sim 0.02$.

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IV.2 Theoretical and Experimental Study of the Field on the Surface of the Earth Scattered by a Buried Object. H.-M. Lee, T.T. Wu, and R.W.P. King, Contracts 68-0404 and N00014-75-C-0648; Research Unit 10.

A new project on the scale model study of controlled source audio magneto-telluric surveys has been initiated. It is the logical continuation of the previous scattering problem in which the obstacle was above the water. In the present case, the scatterer will be immersed in water and will take on different shapes such as strip loops, discs, and other less regular geometries. The purpose is to study how well the boundaries of the objects can be defined by looking at the scattered fields.

A circular pool, four feet high and eighteen feet in diameter, has been installed in the basement of the McKay Laboratory. The skin depth in water will be kept at about 10 cm by changing its salt content. A wooden frame was erected above the tank to support microwave absorbers, the transmitter, and the driving train of the probe set. The probe set consists of a dipole and a shielded loop. It was designed so that the dipole could be modified easily to work at frequencies above, or not too far below, 30 MHz. Initially the system will be operated at 300 MHz. The probe set will be fixed at a height above the water of about 5 cm and can be moved horizontally in a $50 \times 50\ \text{cm}^2$ area around the scatterer. The scatterer is designed to be supported from below and can be lowered from the surface of the water to about 1.5 feet from the bottom of the pool. Although different components of the total fields will be recorded, it is hoped that the lateral variations of the field propagating vertically from the water can be separated and analyzed.

The modification of previously available computer programs for the scattered fields of a loop near a two-medium interface to accommodate complex wave numbers is underway. This program will be helpful in interpreting experimental data.

IV.3 Scattering by a Thin-Wire Cross. R.W.P. King and B.H. Sandler, Contracts N00014-75-C-0648 and DAAG29-79-C-0109; Research Unit 10.

The currents induced by a plane electromagnetic wave in a wire cross with arms with individually unrestricted lengths were determined for normal incidence in both zero and first order in 1975.[1] The formulation was extended to arbitrary angles of incidence specifically for an equi-arm cross in 1977,[2] but was carried out only in zero order, which does not take into account the capacitive coupling between the mutually perpendicular conductors. A complete first-order analysis has now been carried out for a cross with arms with different and unrestricted lengths excited by a field arriving from any angle and polarized in any direction.[3] All coupling effects are taken fully into account. A detailed study has been made of the currents in the equi-arm cross when the angle of incidence is 45°, the electric field is polarized perpendicular to the horizontal member of the cross, and the arm lengths are in the range $kh \leq 3.5$ which includes one even and two odd resonances. The effect of changes in the length of each of the vertical arms has been determined and the critical conditions relating to three-arm and four-arm types of oscillation have been discussed.

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IV.4 Induced Currents in and Scattered Field of Tubular Metal Cylinders of Arbitrary Length and Radius when Excited by a Plane Wave Incident at an Angle. R.W.P. King and B.H. Sandler, Contract N00014-75-C-0648, and S.S. Sandler of Northeastern University; Research Unit 10.

The currents induced on electrically thick $(ka > 1)$ tubular metal cylinders when excited by a *normally incident* plane wave are well-known both for infinitely long tubes[1] and for tubes of finite length[2-5] for both E- and H-polarization. No comparable knowledge is available when the same metal tubes are illuminated by a plane wave arriving at an *arbitrary angle of incidence*. It is the purpose of this project to determine both the currents induced on tubular cylinders and the field scattered by them when illuminated by a plane wave that arrives from an arbitrary direction. The study is theoretical and is based on an extension of the theory and program of C.C. Kao.[6] Computations have been completed for tubular cylinders with the electrical radii $ka = 5$ and 12 and the electrical length $2kh = 20\pi$ at angles of incidence of 30°, 45°, 60° and normal incidence, 90°. Standing waves of surface current have much greater amplitudes when the cylinder is illuminated at an angle.

The possible application of the results obtained and the methods developed to the problem of aircraft recognition is anticipated.

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IV.5 Numerical and Analytical Determination of Fields of Antennas Near an Interface between Two Half-Spaces with Significantly Different Wave Numbers. T.T. Wu, R.W.P. King, and B.H. Sandler, Contracts N00014-75-C-0648 and N00014-79-C-0419; Research Unit 10.

Until recently the theoretical tools available for the study of the propagation of electromagnetic waves in a region composed of two half-spaces filled with two different material media included: 1) the general complex integrals originally due to Sommerfeld for the field of an infinitesimal dipole parallel or perpendicular to the plane boundary, and 2) simple formulas due to Baños for restricted, nonoverlapping ranges that approximate the field. At Harvard a detailed numerical evaluation of the general integrals for the radial electric field due to an electric dipole in a half-space of earth or water bounded by air has been carried out and compared with Baños' approximate formulas.[1,2] Numerical calculations have also been made of the field and the Poynting vector in both regions quite close to the dipole in order to illuminate the excitation of a lateral wave by a dipole.[3]

A great step forward in the analytical treatment of lateral waves has recently been achieved by T.T. Wu who derived a new single formula that accurately represents the exact general integrals for the radial electric field E_ρ over the complete range of frequencies and distances.[4] In this paper, the field in the water or earth is investigated as a function of radial distance from the source for $\epsilon_r = 80$, 20, and 4, over wide ranges of conductivities and frequencies. Special attention is paid to the ranges in which the direct wave from the dipole produces an interference pattern of standing waves when it interacts with the lateral wave. For selected values of the parameters the radial electric field computed from the new simple formula is compared with the field evaluated numerically from the exact integrals. The agreement is excellent when the ratio of wave numbers characteristic of the denser half-space and air is large; quite good even when this ratio is as small as 2.

Comparable formulas for the transverse E_ϕ and vertical E_z components of the electric field have now also been obtained.[5] Comparisons with numerical evaluations of the exact general integrals show excellent agreement when $\rho \geq 5d$.

The importance of the availability of these formulas in the study not only of the propagation but also the reflection and scattering of lateral waves at boundaries and surface irregularities cannot be overestimated. The derivation of similar formulas for the components of the magnetic field is planned.

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IV.6 Lateral-Wave Propagation and Modeling of the Lithosphere. M.F. Brown, R.W.P. King, T.T. Wu, and J.T. deBettencourt, Contracts N00014-79-C-0419 and N00014-75-C-0648; Research Unit 10.

The continuation of work in progress at the time of the last progress report has consisted in: i) the repetition of former measurements of the perturbed $E_{1\rho}$ lateral surface-wave field due to rectangular square wells of air (formed by submerged styrofoam sheets), and ii) new measurements of the perturbed fields due to three classes of objects, namely, square wells of water extending upward from the air-water interface; wedge-shaped objects; and metallic cylinders (both submerged and semi-submerged). The three obstacle types have geometries chosen to characterize, respectively, the following analogues of a real lithosphere: broad plateau, mountain, and submarine/mine.

Both the repeated and the new measurements have been done in a manner which allows the study of the finite size of the model lithosphere in the y- and z-directions. The separation h between the upper metal plate and the air-water interface, formerly held constant, has been varied freely. In the absence of a scatterer along the interface, the $E_{1\rho}$ curve has been examined for the conditions $h \ll \lambda_a$, $h \approx \lambda_a$, and $h \gg \lambda_a$, where λ_a is the air wavelength. The measured field has been shown to follow the calculated field associated with the most recent theoretical expressions for $E_{1\rho}$.[1] The lateral-wave, incident upon the various obstacles mentioned above, shows a localization of scattering effects other than overall amplitude near the vicinity of the scatterers. It has been determined that within the sensitivity range of the receiver no appreciable scattering is evident for submerged cylinders with dimensions up to several multiples of the water wavelength λ_w. A semi-submerged cylinder exhibits a significant scattering pattern generally localized to within two or three wavelengths in front of and behind its cross section.

The rectilinear tank used in the aforementioned studies is in the process of being modified to a semicircular geometry for the investigations of the coming year. This will eliminate troublesome reflections from side walls and will permit a study of directional patterns. A region of variable conductivity has been provided to modify and hopefully reduce reflections of the surface wave from the semicircular boundary. For this a reflection and transmission coefficient will be determined.

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IV.7 <u>Problems on the Propagation and Scattering of Lateral Waves</u>. J.M. Dunn, Contract N00014-75-C-0648; Research Unit 10.

The theoretical existence of lateral waves has been known for a long time.[1] Almost all studies up to this point have centered on a simple source in a dissipative half-space. Recently, Wu and King have published results on this problem using a new method.[2] The technique is interesting since it may allow extensions to some problems previously found very difficult.

One problem, which is interesting from both a theoretical and practical viewpoint, is to see how the lateral wave is modified by a third layer. The dipole source may be in either the lowest layer or in the middle slab layer. If assumptions are made that the magnitudes of the complex dielectric constants of the three materials differ a great deal, the Wu and King method may be applied. Recently, the exact form of the solution has been obtained in a form that may make this approach feasible. To check the analytical results, a thorough numerical study will be made, supplementing the already existing results for the two-layer problem.[3] Such a three-layer problem could model, for example, a silt layer on a lithosphere of rock at the bottom of the ocean.

A second way to generalize the solution is to look at a variety of sources, including dipole arrays and arrays of traveling-wave antennas. Such arrays will increase the directional properties of lateral-wave transmission, making practical applications more feasible. Given the new theoretical results, new useful formulas seem possible. In addition, an experimental study is now being planned to measure the actual field patterns of such arrays.

A third problem of interest is to see how the lateral wave is affected when the interface between the two media is no longer flat but has a variation, such as a bump or a dip. Depending on the nature of the variation, the lateral wave may either continue on in essentially the same manner or be attenuated and scattered a great deal. An analytical study that makes use of the Wu and King method and experimental work in this area are planned.

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IV.8 Subsurface Communication or Heating with Embedded Insulated Antennas. R.W.P. King, Contract N00014-75-C-0648, and S. Prasad of Northeastern University; Research Unit 10.

When an antenna is to be used in a material medium like the earth or a living organism either for purposes of communication and telemetry or for local heating, its configuration is often constrained by the need to insert it with its feeding transmission line into a hole that is very deep compared to its cross-sectional dimension. Usually the antenna and its transmission line are or must be insulated from the surrounding earth or flesh. A theoretical and experimental study has been completed of the properties of insulated antennas embedded at a considerable depth below the surface of a living organism or of the earth.[1,2] Special attention has been given to devising methods of transmitting power for localized radiation or heating. Four different insulated coaxial lines and antennas with interesting and useful properties when inserted in a hole in a general dissipative medium been studied. These are the insulated coaxial line with extended inner conductor, the insulated center-driven dipole with choke section, the insulated sleeve dipole, and the series-connected insulated transmission-line antenna. In order to permit convenient laboratory measurements, models have been designed for use at $f = 600$ MHz with air as the insulator and with salt or fresh water as the ambient medium. Corresponding structures that are much larger for use at lower frequencies in the earth or that are much smaller for use at higher frequencies in living tissue are readily constructed with similar properties.

The analysis, based on the theory of the insulated antenna, show that the insulated conductor embedded in an electrically dense, conducting or dielectric medium is a versatile device for communication or heating in the earth or a living organism. It can be operated as a resonant element or as a traveling-wave antenna and, with appropriate dimensions, is useful at frequencies ranging from the highest to moderately low ones.

Although the theory of the center-driven insulated antenna has been confirmed experimentally, its application to the several practical structures under study involves a number of approximations which require experimental validation. An experimental study of the different insulated antenna-transmission-line structures was carried out and the results show that the theory of the insulated antenna may be used with accuracy to predict the behavior of insulated antennas with complicated structures.

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IV.9 Theoretical and Experimental Study of Electromagnetic Fields and Antennas in Dissipative and Dielectric Cylinders. R. Bansal, Contract N00014-75-C-0648; Research Unit 10.

The investigation of the induced electromagnetic fields inside a finite dielectric cylinder illuminated by a plane wave has been completed.[1] The theoretical solution for the finite dielectric cylinder proceeds in two steps. By taking advantage of the fact that water has a large (in general complex) relative dielectric constant, it has been possible to "decouple" the internal absorption problem from the external scattering problem. First the external problem is solved numerically using a surface integral-equation solution and the tangential magnetic field $\vec{H}_{tan}$ on the surface of the cylinder is computed. This $\vec{H}_{tan}$ then serves as the boundary condition for an analytical eigenfunction solution of the internal problem. Since the internal problem is solved analytically, it was possible to incorporate into the theoretical model the central conducting tube of the experiment without significantly increasing computation time or labor. (The conducting tube was required in the experimental setup to shield the transmission lines leading to the probes.) The basic procedure can be iterated for improved accuracy. The computer implementation of the method is very economical since only a single integral equation needs to be solved numerically. The iterative scheme used in the method shows rapid convergence for dielectrics characterized by a large real permittivity *and* a moderately high loss tangent; hence, the method is particularly suitable for biological applications. The iterative scheme is only partially successful at best when applied to a dielectric cylinder possessing a large real permittivity but a small conductivity (e.g., distilled water). This breakdown of the iterative scheme is believed to be closely related to the internal "resonances" of the dielectric cylinder. A comparison of sample calculations for salt-water cylinders and corresponding experimental results show good agreement.[2,3] The experimental measurements were carried out at 100, 300, and 600 MHz.[4] The conductivity of the 50 cm long column of water was varied from approximately zero to 3.5 S/m.

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IV.10 <u>A Theoretical Study of the Rhombic Antenna as an EMP Simulator.</u>
H.M. Shen and R.W.P. King, Contract N00014-75-C-0648; Research Unit 10.

In order to obtain greater insight into the physical phenomena associated with a transmission-line type EMP simulator (see Topic 11), it has seemed desirable to make use of a structure that permits an accurate analytical determination of the currents in the conductors and of the electromagnetic fields they generate, while still approximating the actual simulators in general shape. Such a structure consists simply of the two-conductor rhombic antenna. It is well known that this type of rhombic antenna has broad-band properties. However, early analyses have been concerned exclusively with the far field and not with an accurate determination of the currents in the conductors and especially of the field between them which is of interest in its possible application as an EMP simulator. Note that in the rhombic simulator the currents at all frequencies are confined to electrically thin conductors that, in effect, are located along the edges of the metal-plate or wire-mesh simulators where the largest current density is to be found.

A complete analysis has been made of the two-conductor rhombic antenna as an EMP simulator.[1] The distributions of current along the conductors and the electric field in the working space bounded by them have been determined. They are very well approximated by quite simple formulas, the zero-order approximations. When the structure is terminated in the characteristic impedance, the currents are very nearly traveling waves and this is true over a wide frequency band. At low frequencies when the distance between conductors is everywhere electrically small, the structure behaves like a simple transmission line. As the frequency is raised to intermediate and high values with the wires several wavelengths apart at the center of the simulator, the traveling-wave nature of the current and the associated electric field is still quite well maintained. The terminating impedance continues to be effective at the high frequency even though a significant fraction of the power supplied by the generator is radiated. The electric field in the working space bounded by the conductors exhibits a reasonably constant amplitude with a low standing-wave ratio of 1.5 at all frequencies.

An experimental study of the rhombic EMP simulator is discussed under the following topic.

<u>Reference</u>

1. H.M. Shen and R.W.P. King, "The Rhombic EMP Simulator," *IEEE Trans. Electromagn. Compatib.*, accepted for publication.

IV.11 <u>Fields and Currents and Charges on Obstacles in a Parallel-Plate Simulator at Selected Frequencies and with Pulse Excitation</u>. H.M. Shen, R.W.P. King, and T.T. Wu, Contracts F29601-81-K-0010 and N00014-75-C-0648; Research Unit 10.

The purpose of an EMP simulator is to provide an electromagnetic environment for an aircraft, missile, or other obstacle that approximates an electromagnetic pulse from a nuclear explosion in the atmosphere.

Extensive measurements made in the Harvard model simulator have shown that at both low and high frequencies the electromagnetic field in the parallel-plate region exhibits a fairly low standing-wave ratio of the order of two or less.[1] On the other hand, in an intermediate range of frequencies very minima can be observed with associated standing-wave ratios of 30 or greater.[2] It is of interest to determine the current and charge densities induced on metal objects at different locations in such a standing-wave pattern and to compare these with the corresponding quantities when the inducing field is a plane traveling TEM wave. Earlier studies have shown that the distribution of the surface density of charge is particularly sensitive to the nature of the incident field. Accordingly, measurements have been made of the density of charge on the surface of a tubular metal cylinder with $ka = 0.916$ when located at successively different points in a high standing-wave field in the simulator.[3] The measurements were made specifically at the "notch" frequency, $f = 271$ MHz, when an extremely deep minimum exists in the standing wave. Theoretical distributions of the surface charge density when the exciting field is an ideal traveling plane wave were computed using the theory and program of C.C. Kao.[4] A comparison of the theoretical and experimental results shows that when an electrically large obstacle of the simplest form is located in a standing wave that includes TEM and TM waves with a deep minimum, the distribution of the induced surface density of charge not only differs from that induced by a traveling TEM wave, but depends on the location of the cylinder in the standing wave. The charge distribution may have the form of a traveling wave on the shadowed side of the cylinder and a standing wave on the illuminated side when the rear of the cylinder is located at a minimum, or precisely the reverse when the center of the cylinder is at the minimum.

The amplitude of the charge density half-way up the cylinder on its shadowed side may vary by a factor as large as 4 as the cylinder is moved from a location with the minimum in the exciting field at the rear to a location with the minimum at the front.

In order to gain greater insight into the electrical properties characteristic of all EMP simulators of transmission-line type, including the Harvard model simulator, theoretical and experimental studies have been made of a modified and simplified simulator--the two-conductor rhombic EMP simulator. Since the wires of the rhombic antenna are located to correspond to the edges of the metal plates of the Harvard simulator (HES), where the largest current density is to be found, the major properties of the HES should also characterize the rhombic simulator (RS), and the observations made on the RS (which is relatively easy to investigate theoretically and experimentally) should be comparable with the corresponding data for the HES. The continuous-wave investigation of the RS at selected frequencies has been completed and a comparison made between the theoretical and experimental results obtained for the RS and the earlier measurements on the HES.[5]

With the completion of the CW study of the RS, attention was directed to the properties of the RS with pulse excitation. This involved the adjustment of the pulse equipment and the writing of special programs for acquiring pulse wave-forms and processing the data for different purposes. In order to record the very extensive numerical data, especially the variety of waveforms, a printer was added to provide the system with the capability of graphical representation. The system for pulse operation has been working very well, and a study has been begun of the pulse currents propagated along the rhombic tubes and the distribution of the generated electromagnetic pulse along the ground plane. It is anticipated that a complete understanding of the field in the RS under pulse operation will have been achieved shortly. The RS will then be replaced by the metal plates of the HES and this will be investigated in detail with pulse excitation.

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IV.12 The Cylindrical Dipole as a Probe for Measuring Electromagnetic Pulses. R.W.P. King, Contract N00014-75-C-0648; Research Unit 10.

In order to measure the components of the electromagnetic field, probes or sensors must be used that have known characteristics in their dependence on their dimensions and on the frequency. For use in the measurement of electromagnetic pulses, the probe must be frequency-independent over the range of frequencies contained in the pulse. The electrically thin cylindrical dipole is a well-known and much used probe.

Formulas and tables of its characteristics for both transmission and reception are generally available over a very wide range of electrical lengths and radii. These formulas have been employed to determine the frequency dependence of the dipole.[1] It is shown that the cylindrical dipole is frequency-independent in the measurement of the time derivative of the electric field ($\partial E/\partial t$ in the time domain or ωE in the frequency domain) and not directly of the electric field. In the time domain the electric field can be determined by means of an integration with respect to the time. In the frequency domain the known characteristics of the cylindrical dipole make it useful for measuring the electric field. The possible application of the dipole as a calibration standard for testing other types of sensors is also illustrated.

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IV.13 Large Antenna Arrays on Curves. T.T. Wu, Contracts N00014-75-C-0648 and DE-AS02-76ER03227, and A. Grossmann of CNRS, Marseille, France; Research Unit 10.

Attempts are currently being made to analyze in more detail a novel type of antenna array, consisting for example of a large number of dipoles arranged along a closed curve. The approach used is to apply the method of Fermi pseudopotential to Maxwell's equations. As a first step in this direction, the Fermi pseudopotential for the Helmholtz equation has been generalized from three to five dimensions. It is found that the underlying structure changes qualitatively and profound mathematical problems need to be answered.

V. SIGNIFICANT ACCOMPLISHMENTS REPORT

V.1 Anomalous Temperature-Dependence of the Elastic Constant B at the Nematic-Smectic A Phase Transition in Binary Mixtures of 8OCB-6OCB.

M. Fisch, L. Sorensen, and P.S. Pershan; Research Unit 4, SOLID STATE ELECTRONICS.

The nematic to smectic-A transition is one of the major unsolved problems in statistical physics. Extensive measurements in a number of laboratories have been made on the critical behavior of, the heat capacity, the correlation lengths, and the elastic constants of diverse materials on both sides of the phase transition. The pattern of results from all of these measurements is *not* consistent with any accepted theory of this transition. Recently, Professor David Nelson and Dr. John Toner proposed an explanation to account for this effect, and we have shown that for a certain range of concentrations in mixtures of $(8OCB)_x(6OCB)_{1-x}$ the elastic constant B behaves in a way consistent with their hypothesis.

Based on a dislocated mediated model for the melting of the smectic-A phase, Nelson and Toner were able to argue that although the correlation lengths $\xi_\parallel$ and $\xi_\perp$ diverge, $\xi_\parallel/\xi_\perp^2$ approaches a constant value. From previously exciting theories of anisotropic scaling, the smectic-elastic constant B is predicted to vary as $\xi_\parallel/\xi_\perp^2$. Thus, the Nelson-Toner model requires a specific and rather delicate relationship between two diverging parameters. They also predict that B should vanish discontinuously at the transition. Although previous measurements are not consistent with this hypothesis, the natural explanation is that $B = B_0 + B_1(t)^\phi$ and since B_0 is sufficiently small, it is possible to mistake the proposed behavior for one in which B_0 is rigorously zero. Using our recently developed technique for light scattering from the free surface of a horizontal smectic liquid crystal, we have been able to measure the shear sound speeds at the nematic to smectic-A phase transition and obtain a direct measure of the critical behavior of B. In particular, for certain mixtures of 8OCB-6OCB the value of B_1 becomes much smaller than values commonly found in most materials. In such mixtures, it should therefore be considerably easier to determine whether or not there is a small residual constant part (i.e., B_0) for a B that is *apparently* vanishing as t approaches zero. Measurements made on three different concentrations obtain values of B_0 of the order of 10^7 ergs cm^{-3}. There are a number of theoretical relations between this value of B_0 and other parameters that enter into the theory of the nematic to smectic-A phase transition and this value of B_0 is perfectly consistent with all of those. Furthermore, it has been possible to develop a theoretical criterion by which one can judge whether or not other experiments should have detected the consequences of the Nelson-Toner hypothesis. In all previous experiments this criterion was not satisfied and the Nelson-Toner relation should not have been observed.

To summarize, the significant accomplishment in this report period is an experimental result that strongly supports a novel suggestion to explain the nature of nematic to smectic-A phase transition. In view of the fact that this phase transition remains one of the major unsolved problems in statistical physics and in view of the fact that there does not now exist *any* other compelling proposal to explain the diverse experimental results, this experiment defines a future direction for liquid crystal research.

V.2 Picosecond Laser Interactions with Silicon. J.M. Liu, H. Kurz, and N. Bloembergen; Research Unit 6, QUAN[illegible] ELECTRONICS.

The question of the mode of interaction of laser beams with silicon has been settled in favor of the "simple thermal model." More exotic theories of electron-hole plasma confinement or Bose-Einstein plasma condensation[1,2] cannot be reconciled with most experimental data. While many laboratories have studied the problem of laser heating and annealing with nanosecond pulses, the JSEP program at Harvard was first in the experimental investigation of picosecond irradiation of silicon. We have observed the emission of electrons and positive ions, the change in reflectivity, as well as the surface morphology changes induced at the surface of single crystal of silicon, as well as the change in transmission in a silicon film on sapphire. The effects were studied as a function of the energy fluence of the incident heating pulse at both a green wavelength ($\lambda = 530$ nm) and an ultraviolet wavelength ($\lambda = 265$ nm). The probing wavelengths for reflection and transmission were these same as well as the infrared wavelength ($\lambda = 1.06$ μm).

The data shows conclusively that melting of thin surface layer occurs during a 20 ps pulse. Subsequent resolidification rates depend very sensitively on the energy fluence. If the resolidification front travels faster than 20 m/sec, an amorphous phase may be formed. It has been established that the thermal equilibration time between the dense hot carriers and the lattice in silicon is less than 10^{-11} sec, with a value of about 10^{-12} sec being most likely. Furthermore, the density of plasma never exceeded 2×10^{21} electrons/cc, limited by the rapid Auger recombination rates.

The rate of phase transformation, such as melting vaporization and resolidification, may now be studied on a picosecond time scale. Deviations from thermal equilibrium in condensed phases appear to require still shorter times. Picosecond irradiation of metallic mixtures can produce melting of alloys. Subsequent fast resolidification has been observed to freeze the alloy composition in an amorphous solid configuration.

Time resolved studies in materials and surface science on a picosecond time scale are now open to experimental investigation.

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V.3 Collision Induced Coherence. A. Bogdan, M. Downer, and N. Bloembergen; Research Unit 5, QUANTUM ELECTRONICS.

We have demonstrated the creation of a coherent light beam caused by collisions in a mixture of Na-vapor and helium gas.[1] The experiment was performed by using two tunable dye laser. The dye laser at the fixed frequency ω_1, tuned near one of the yellow D-lines of Na with an offset of about 1 cm^{-1}, produced two beams in the vertical plane. The second dye laser at ω_2 produced a beam in the horizontal. Due to four-wave non-linear mixing, light appeared in a new direction in the horizontal plane. The frequency of this light is $2\omega_1 - \omega_2$. The frequency ω_2 is tuned slowly in the vicinity of ω_1. Resonances appear in the intensity of the fourth beam for $\omega_1 = \omega_2$ and for $\omega_2 = \omega_1 \pm 17$ cm^{-1}, but only if a sufficient pressure of helium buffer gas is present. The creation of a coherent light beam due to collisions sounds paradoxical, as collisions are generally thought of as a coherence or phase-destroying mechanism. This paradox is resolved as follows. In the absence of the collisions, there are many theoretical channels (or Feynman diagrams) which contribute to the four-wave light scattering. Certain combinations of these diagrams interfere destructively, and yield a vanishing result in the absence of collisions. The collisions destroy the destructive interference, and the fourth light beam emerges.

This new process verifies a fine point in the quantum theory of nonlinear susceptibilities in the presence of damping. Furthermore it provides a new handle in the study of details of collisional processes.

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V.4 Incentive Optimization Problem. P. Luh, T.S. Chang, L.D. Servi, and Y.C. Ho; Research Unit 9, INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION.

The most significant accomplishment during the past years has been the unification of our past work in the area of nonclassical information structure with the problems of incentives and Stackelberg optimization.

The overall approach has been to view the incentive problems as a coupled control problem involving two or more persons. First, the deterministic version of the problem is analyzed. In particular, the role of dynamics and information structure is detailed.[1] The basic concepts developed is then extended to stochastic case where its relationship to the economic literature is pointed out.[2]

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V.5 Electromagnetic Wave Propagation Along a Plane Interface Between Two Half-Spaces. T.T. Wu and R.W.P. King; Research Unit 10, ELECTROMAGNETIC PHENOMENA.

The theory of electromagnetic wave propagation along a plane interface between two half-spaces and its application to practical problems in communication both over and in the earth have been subjects of interest and extensive study since the early work of Sommerfeld and his students beginning in 1909.[1] Exact general integrals for the fields near the interface in both media due to horizontal and vertical dipoles have been available for over fifty years and many approximate analytical solutions in restricted ranges have been provided. The most extensive work in this field is that of Baños.[2] More recently, attention has been directed toward the numerical evaluation of the complex integrals with high-speed computers in order to obtain more accurate results over wider ranges of the variables and parameters than were provided by the available approximate formulas. Early contributions from Harvard were to the propagation of electromagnetic waves from and to antennas in sea water near the surface.[3-5] More recently, a systematic theoretical, numerical, and experimental study was begun of propagation along surfaces that correspond to those existing on the earth--the sea, a lake, soil, etc. In order to provide a comprehensive picture of the propagation of waves from horizontal electric dipoles in all types of material found near the earth's surface, extensive computations have been reported.[6-9] These include boundaries between air and materials with a wide range of relative permittivities and conductivities at frequencies that extend from 10 to 10^9 Hz and over distances from 10 cm to 100 km. In the numerical calculations points were evaluated at the logarithmically convenient steps of 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100 (meters/kilometers). It was thought that the graphs and tables[9] provided all of the information necessary for a comprehensive and detailed physical picture of lateral-wave propagation. It turned out that this was not the case.

Because the complexity of the general integrals obscures the physical properties of lateral-wave propagation and makes their numerical evaluation long, difficult, and expensive, a systematic attempt has been made to derive new formulas for the components of the electromagnetic field generated by horizontal electric dipoles in a dissipative medium near its plane interface with air. Each component is to be represented by a single, simple formula over the entire range of interest of all of the parameters and variables. This project has been successful. Such formulas are now available[10,11] for all three cylindrical components of the electric field. They involve only simple exponential functions and error functions and their accuracy has been checked in detail against numerical calculations from the general integrals.

The significance of these new formulas is considerable. Simple inspection revealed that there must be an interference pattern in the amplitudes and phases of the components due to the interaction of the clearly separated lateral and direct waves. Detailed and extensive computations have for the first time demonstrated the existence of such patterns in all media.[10] Recomputation from the general integrals with suitably and greatly reduced intervals of distance has shown complete and very close agreement with the simple approximate formulas. Significantly, the time required for the data from the new formulas is measured in fractions of a minute, that from the general integrals in many hours.

The new, accurate and simple formulas for the electric field in lateral-wave propagation open a hitherto closed door to the detailed quantitative study of lateral waves and the physical understanding of their properties.

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